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PROBABILISTIC ASSESSMENT OF THE PICKERING UNIT 4 CORE FOR PRESSURE TUBE CRACKING DUE TO HYDRIDE BLISTER FORMATION

Report No. 88-324-K
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ABSTRACT

The purpose of this report is to provide detailed documentation of the work carried out for the Deuterium Ingress Task Group for the assessment of the remaining life in the Pickering reactors. The probability of having pressure tubes in the central core containing blisters sufficiently large that initiation of delayed hydride cracking could occur has been computed based on a refinement of a previous computer model and a new treatment of some of the input parameters. Key assumptions of this work are that the deuterium pickup rate underwent a transition after 91000 EFPH and that the deuterium measurements obtained in the microsampling campaign on P4 at the end of 1987 were representative of the entire core. The assessment indicates that the probability of having no critically blistered tubes drops substantially during the next few years of reactor operation.

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EXECUTIVE SUMMARY

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This report provides detailed documentation of the work carried out for the Deuterium Ingress Task Group for the assessment of the remaining life in the Pickering reactors. The probability of having pressure tubes in the central core containing blisters sufficiently large that initiation of delayed hydride cracking could occur has been computed based on a refinement of a previous computer model and a new treatment of some of the input parameters. Key assumptions of this work are that the deuterium pickup rate underwent a transition after 91000 EFPH and that the deuterium measurements obtained in the microsampling campaign on P4 at the end of 1987 were representative of the entire core.

CONCLUSIONS:

1. This assessment indicates that there will be a significant reduction of the reliability (the probability of having no critically blistered tubes in the core) over the next several years.

2. Sensitivity studies have shown that deuterium ingress scenarios and garterspring position information have a significant influence on the assessment. Uncertainties in the initial hydrogen concentration of the tubes and in the heat of transport of hydrogen have a smaller influence.

RECOMMENDATIONS:

1. Establish models of deuterium pickup to significantly improve on the quality of the assessment for decision making purposes.

2. Put more effort into measuring and understanding garterspring position information.

3. Accelerate underlying research on blister growth and fracture.

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To D.W. Souther
Manager
Nuclear Systems Department

PROBABILISTIC ASSESSMENT OF THE PICKERING UNIT 4 CORE FOR PRESSURE TUBE CRACKING DUE TO HYDRIDE BLISTER FORMATION

1.0 INTRODUCTION

The objective of this report is to provide a record of the details of the analysis of the Pickering 4 reactor that was carried out in support of the Deuterium Ingress Task Group (DITG) assessment of the remaining reactor life following the P4 pressure tube microsampling at the end of 1987. This analysis was done using a computer model for probabilistic reactor assessment of blisters which has been under development at OHRD since the end of 1985. A complete description of the model has been reported elsewhere/1/. In this report, some of the significant differences between the model used for the assessment and both former and current models are highlighted.

The model requires five basic inputs which are described in detail in the appendices of Reference 1. The main body of the report includes a short model description (including some of its limitations), the results of the assessments carried out (including some of the key sensitivity analyses performed) and an interpretation of these results.

2.0 PROBABILISTIC ASSESSMENT MODEL OUTLINE

The model has been developed in several stages and was previously used to support REFAB and SLAR assessments/2,3/. Those assessments were limited to the estimation of the number of tubes in a reactor containing blisters of all sizes. When the results of the deuterium determinations in the pressure tube removed from P3 - L09 in July 1987 became available, the model development was accelerated by substituting an approximation for the bulk concentration at which failure will occur. The concept of a critical blister size that would lead to DHC initiation in a tube was introduced (see Reference 1: Appendix 1) and the model was altered to include calculations of the probabilities of critical blister formation.

The basis for the operation of the model has not changed. In order to have either blisters or critical blisters, two conditions must be fulfilled:

1. The pressure tube must contact the calandria tube.

2. The equivalent hydrogen content in the bulk of the tube near the contact point must exceed a threshold value (different for blisters and critical blisters).

Blister growth modeling used to determine thresholds for critical blisters is described in Appendix 2 of Reference 1.

The main refinements in the model compared with earlier versions are:

1. Deterium pickup rate and blister threshold concentrations are a function of the PHT temperature local to the contact.

2. The contact is allowed to spread axially as a function of time. However, only spreading towards the outlet end was considered in this assessment.

The steps in the program to calculate the probabilities of critical blister formation are described schematically below;

1. Selection of a random set of garterspring locations. The details of this procedure are discussed in Appendix 3 of Reference 1.

2. Selection of a value of the random variable initial hydrogen.

3. Calculation of the location of the contact on Sakaguchi's nomogram. All the contact work is explained in Appendix 4 of Reference 1.

4. Calculation of the time to contact assuming that the channel is in the central core.

5. Scaling of the contact time if the channel is in the intermediate or outer zone.

6. Calculation of contact location at time of contact.

7. Calculation of the position of the outlet end of the contact at each year after initial contact. The spreading model is outlined in Appendix 5 of Reference 1.

8. Calculation of the temperature at that location.

9. Calculation of the time it takes at that location for hydrogen to reach the threshold for blister formation. This requires knowledge of the deuterium pickup rate as a function of time at that temperature and location.

10. Calculation of the time it takes at that location to reach the hydrogen threshold for critical blisters.

11. Storage of the shortest time for both blister formation and critical blister formation for that time and investigation of what happens one year later by repeating the same. The process (7-10) is repeated as often as necessary.

12. Calculation and storage of the earliest time for blister formation and critical blister formation.

13. Repetition of the process. (Back to 1).

These steps complete the Monte Carlo process. The post-processing includes summarizing the statistics of the inputs used for all the realizations and plotting the results.

3.0 APPLICATION TO P-4 DEUTERIUM MEASUREMENTS

This section of the report deals with the particular inputs and programming developments carried out to produce an assessment of Pickering Units 4 following the analysis of the microsamples removed from the tube inner surfaces of twenty channels in P4 at the end of 1987.

3.1 Deuterium Ingress

Assumptions were made in conjunction with the Deuterium Ingress Task Group as to the ingress scenario that would be used for the assessment. The following key assumptions were used:

1) The deuterium ingress is piecewise linear; and its rate changes from a low primary rate (dependent on temperature) to a higher secondary rate at thirteen years of operation (91,000 EFPH). This assumption was partially based upon a previous analysis of tubes removed from P3 and P4 over the last several years (P3 L09 and P4 K10 in particular) which indicated a possible interpretation of the results based upon a thirteen year transition.

2) The secondary rate is also taken to be temperature dependent towards the outlet from the 4 m location of the pressure tube. It is temperature independent between the inlet end of the channel and the 4 m location.

3) The form of the distribution of the secondary rates at a given temperature is assumed to be Weibull. The method by which the parameters of the distribution were established will be shown in Section 3.3.1.

4) Primary and secondary pickup rates are taken to be uncorrelated. Also there are no correlations assumed between tube chemistry (characterized by the iron content, for example) and the pickup rates.

3.1.1 Establishment of Weibull Parameters based on P4 Deuterium Analyses

The deuterium measurements obtained with samples (free of oxide) from the 4 and 5 m locations were analyzed to produce a distribution of secondary pickup rates for use in the probabilistic assessment. The values used are shown in Table 1. Also included are the corresponding values obtained from punched samples of P3-L09/4/ which were included in the analysis. Table 2 includes the values of the mean and standard deviation calculated for different groupings (high power, all power, with and without P3-L09). The inclusion of P3-L09 at the 4 m location makes virtually no difference to the means and standard deviations. At the 5 m location, the inclusion of the P3-L09 data shifts both the mean and the standard deviation to higher values with the greatest effect being on the standard deviation.

Parametric representations of the deuterium distributions at the 4 and 5 m locations were obtained by fitting Weibull distributions to all the 4 and 5 m observations by matching the first and second moments (mean and variance) of the distributions. The Weibull parameters derived for the distributions of deuterium at the 4 and 5 m locations are shown in Table 2. Values of

the lower cutoff were determined by varying the cutoff and visually observing the goodness of fit of the calculated distribution to the data on a cumulative probability plot. The final fitted distributions are shown in Figures 1 and 2.

Secondary pickup rates were determined by using the Weibull parameters determined above and converting them to hydrogen equivalent (dividing cutoff and scale parameters by 2), subtracting from the cutoff an estimate of the pickup due to the primary rate during the first 91,000 EFPH, and then dividing cutoff and scale parameters by 2.06, the operating time in 7000 hour years beyond 91,000 hours. For the 4 m location, the estimated pickup due to the primary rate/3/ was slightly greater than the cutoff of the fitted distribution and consequently the cutoff for the secondary rate was taken to be zero (in the probabilistic program, the secondary rate is not allowed to fall below the primary rate). The resulting Weibull parameters for the rates, expressed in hydrogen equivalent per 7000 EFPH year, are given in Table 2.

As noted in Section 3.1 above, in doing the assessment of P4, the temperature dependence of the secondary pickup rate was modeled towards the outlet from the 4 m location. This was done in the program by linearly interpolating the temperature dependence of each of the Weibull parameters based on the values at the 4 and 5 m locations. Therefore the distribution of the assumed secondary pickup rate changes slowly from that at 4 m to that at 5 m. For points towards the inlet from the 4 m location, the 4 m secondary pickup rate distribution was applied.

3.2 Initial Hydrogen Contents

The distribution of initial hydrogen content was also assumed to be Weibull as in References 2 and 3. In previous reports the hydrogen analyses from history dockets for the first and last tube of each ingot were used. However, more recent analysis results of tube offcuts appear to be higher than the history docket information by about 1.3 ppm/5/. Since the complete statistical analysis of the new results was not available, the mean used in the previous reports was increased by 1.3 ppm and the variance was assumed to remain the same. Weibull parameters were established by matching of the first and second moments of the distribution. This resulted in the following set of parameters:

cutoff 0.0 ; shape factor n = 2.3 scale factor sigma = 7.45

The resulting cumulative distribution is shown in Figure 3. During the operation of the program additional limitations on the possible initial hydrogen concentrations were imposed. All selected random values above 20 ppm were set to 20 and values less than 0.5 ppm were set to 0.5 ppm.

3.3 Garterspring Position Distribution

Data from P3 and P4 were combined and a synthetic distribution was constructed as described in Reference 3 using the most recent information available at the time of the analysis/6/. The comparison of the synthetic distribution and the observations, as shown in Figures 4, 5 and 6 clearly demonstrates that the synthetic distribution is a good representation of the actual distribution except that it is smoother over the whole range of garterspring displacements.

3.4 Other Model Parameters

The mean time to contact for a given set of garterspring positions was determined as described in Reference 1. This method is consistent with the application of CRNL 1993 design equations and the ABAQUS finite element code as used by Sakaguchi/7/.

The spreading of contact following initial contact followed the algorithm developed by Holt and described in more detail in Reference 1 Appendix 5. For the P4 case, only spreading toward the outlet end of the channel was taken into account in the model. A limit of 525 cm (from the inlet) was placed on the outlet position of contact. In fact, with this spreading model and for the 15 to 20 year period, there is very little spreading beyond 500 cm. This was checked by evaluating the outlet position of contact using the same subroutine that was used in the assessment program.

The heat of transport for hydrogen, which was used for both the blister growth modeling and the determination of the threshold for blister formation, was taken to be 20,900 J/mole. This value is less than the values quoted in the literature/8,9/ of 23,800 to 25,100 J/mole but is more consistent with recent results obtained in experiments at the University of Toronto/10/.

Assumptions associated with the blister growth modeling, which was used to produce the table of critical blister thresholds (Table 3) as a function of both pickup rate and PHT temperature, are described in Reference 1 Appendix 2. A single set of thermal boundary conditions at the contact between pressure tube and calandria tube was modeled.

4.0 RESULTS

Assessments were carried out for the central core and for the complete reactor. In addition, some sensitivity studies were carried out using variations of the input assumptions. In this section, the results are separated into those used for the DITG assessment and the remaining analyses.

4.1 Deuterium Ingress Task Group Assessment

The results of the assessment carried out for the central core channels (184 tubes) are shown in Figures 7. The average number of blistered tubes is seen to increase starting at about 14 years (98,000 EFPH) and the number of tubes with blisters exceeds 10 shortly after 16 years. The estimate of the number of tubes with critical blisters begins to increase at 16 years and exceeds one sometime between 17 and 18 years.

The uncertainty in the estimated number of tubes, shown in Figure 8, is the uncertainty associated with the application of the probability per tube, calculated using the Monte Carlo technique, to the 184 tubes in the central core. It is the uncertainty associated with the binomial distribution. In other words, if there were 1000 reactors in the same condition as Pickering 4, although the average number of blistered tubes per reactor would be given as in Figure 7, any given reactor would have an integral number of blistered tubes. This number of tubes per reactor can vary significantly about the average as given by Figure 8, the standard deviations being a measure of the width of the distribution. It cannot be known how far the number of blistered tubes in Pickering 4 is from the estimated average. This standard deviation is derived assuming that the calculated probability per tube (the result of the Monte Carlo procedure) has no uncertainty associated with it.

Another measure of the state of the reactor core is the reliability, defined as the probability of having no tubes with critical blisters in the core. The results of this calculation for the central core are shown in Figure 9. They indicate that the reliability starts decreasing before 16 years of operation and that after 19 years there is less than a 1% probability of having the central core free of critically blistered tubes.

The analysis has been extended to the complete core using the assumptions that the deuterium pickup rates and the temperature distributions along the channels are identical to the central core channels and that the garter spring positions measured on the central core channels are representative of the positions in the other zones (not the case in the complete reactor data sets available). The times to contact for tubes in the intermediate and outer zones are scaled according to the method used in previous assessments/2,3/. Estimates of the numbers of tubes containing blisters or critical blisters are shown in Figure 10 and 11. There is close to a 50% increase in the estimate at any given time when compared to the estimate for the central core alone. There is, of course, an accompanying decrease in the reliability for all times beyond and including 15 years (105,000 EFPH) as indicated in Figure 12.

The assumptions used in evaluating the whole core may not be conservative. In terms of deuterium pickup observations at the 4 and 5 meter locations, several of the outer channels are among those with the highest levels. (B16 had the highest level at the 5 meter position). The temperature dependence of the pickup also needs to be factored in correctly by allowing outer channel temperatures to be lower than the central core channels. Using the reduced temperature would slightly reduce also the threshold levels for both blister formation and critical blister formation. Another area of non-conservatism is in the assumption of the garterspring positions. Based on previous observations from Bruce 6 and Pickering 7, it is likely that the outer channel springs are considerably more displaced than the central core springs. This would lead to a greater probability of contact in the outer channels than would be produced using the assumptions here.

4.2 Sensitivity Studies

The sensitivity of the assessment to deuterium pickup rate, initial hydrogen content, garterspring positional information and the heat of transport was examined by making several different computer runs.

4.2.1 Effect of Deuterium Pickup Rate

The effect of a reduction in the pickup rate was tested. The Weibull parameters for the scale factors of the best fit to the data at the 4 and 5 m locations were reduced by 25%. The effect of these changes on the cumulative probability of the modeled deuterium concentration is shown in Figures 13 and 14. The resulting assessment for the central core of P4 is shown in Figures 15 and 16. The time required to reach the 50% reliability estimate for the central core is increased by about one year.

4.2.2 **Effect of Initial Hydrogen**

The effect of the 1.3 ppm reduction in the estimate of the mean of the initial hydrogen content of the tubes was also examined. The reliability for times beyond 15 years was increased slightly by the 1.3 ppm reduction although the 50% point appears to be changed by only a few months (Figure 17).

4.2.3 **Effect of Garterspring Positions**

The sensitivity to garterspring positions was examined using an earlier version of the program in which the treatment of the deuterium pickup was slightly different in that the cutoff for the secondary pickup rate was set to zero. The effect of different choices of garterspring positional information on the assessment can be seen by comparison of several different runs. The garterspring information used was that available before the microsampling of P4/11/. Four different choices of garterspring positional information were run. These were:

1) P4 G/S database
2) P3 G/S database
3) Combined P3/P4 database
4) Synthetic distribution based on P3/P4 combined.

There was a significant difference in the assessment associated with the P4 G/S database as compared to the P3 G/S database difference. This is shown in Figures 18 and 19. (The differences shown in the figures are not strictly just garterspring effects because the initial hydrogen distribution was also slightly different since the P3 G/S run also used P3 initial hydrogen information. However, the difference in initial hydrogen between these two runs was much smaller than the 1.3 ppm change examined above. Therefore, the major effect here is the G/S difference). Inclusion of more recent garterspring information has not changed the tendencies exhibited above, i.e. P3 appears to be significantly worse in terms of contact frequency than P4 and this leads to a higher probability of critical blister formation for any particular operating time.

The result for the synthetic distribution was very close to the combined database result as shown in Figure 20 and 21. (Pickup rate for these two runs was different from that used for the P3/P4 G/S comparison above).

4.2.4 **Dependence on Heat of Transport Q***

The effect of changing the value of the heat of transport from 20,900 J/mole to 25,100 J/mole was also examined using the same early version of the program as in 4.2.3. Changing Q* influences the threshold for both blister formation and critical blisters.

The effects are illustrated in Figures 22 and 23. As expected, the higher value of the heat of transport is more severe. However, the sensitivity to this alteration is less than that for either pickup rate or garterspring position distribution.

5.0 DISCUSSION

This assessment of P4 indicates that, over the next several years of operation, there is a significantly increasing probability of having pressure tubes with blisters and with blisters large enough to initiate cracking in the tube. This message was presented to the DITG at the time these assessments were carried out.

The assessment is somewhat sensitive to the inputs chosen. In particular, the sensitivities to both deuterium pickup rates and garterspring distribution are significant. This fact implies that in order to improve on the quality of the assessment, better information on both pickup rate and garterspring positions is required.

The limitations of the model used to generate these results have been pointed out in an earlier report/1/ and the test of this report. Recently, a newer model (allowing spreading in both directions) has been developed. More flexibility in the type of deuterium pickup scenario is allowed in the newer model. Separate calculations of the probabilities of blisters in channels with east and west inlets can be carried out in order to recognize the apparently different garterspring distributions in the two cases. This separation produces a better estimate of the reliability.

6.0 CONCLUSIONS

A sophisticated assessment of the state of the core of the Pickering Unit 4 reactor with respect to hydride blisters in pressure tubes has been carried out. A probabilistic model under development for some time has been used to make the assessment. The model has only been described briefly since a more detailed description is available elsewhere/1/. The deuterium microsampling results obtained from P4 at the end of 1987 were a key input in this assessment. A key assumption of the assessment was that a transition in deuterium pickup rate occurred after 91,000 EFPH.

The assessment indicates that there will be a significant reduction in the reliability over the next several years.

Studies indicate that the assessment is sensitive to deuterium pickup scenario and garterspring position information. It is less sensitive to uncertainties in initial hydrogen concentrations and the heat of transport of hydrogen in pressure tubes.

7.0 RECOMMENDATIONS

1. Establish models of deuterium pickup to significantly improve the quality of the assessment for decision making purposes.

2. Put more effort into measuring and understanding garterspring position distributions.

3. Accelerate underlying research on blister growth and fracture.

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TABLE 1

Deuterium Measurements from P4 Microsampling

Channel	4 m (ppm)	5 m (ppm)
HIGH POWER		
L13	11.7	31
H13	13.7	18.9
J09	6.1	16.6
G11	17.6	21
M08	7.6	
O12		20
Q15	12.5	
L11	11.9	
F08	15.2	
O08	9.8	15.9
R16	13.3	14
F11	27	28
Q10	8.6	19.7
F06	12	15.5
LOW POWER		
N01	8.1	
Q21	8.8	8.3
M01	9.5	11.7
B16	22	41
D19	22	26
W09	6.4	9.6
P3L09	8	48

TABLE 2

Derivation of Weibull Parameters for Pick-up

Means and Standard Deviations (S.D.) of Observations

Selected Channels	4 m Location Deuterium MEAN PPM D	S.D. PPM D	5 m Location Deuterium MEAN PPM D	S.D. PPM D
High Power P4	12.8	5.27	20.1	5.5
High Power + P3L09	12.5	5.22	22.6	9.9
All P4	12.8	5.73	19.8	8.7
All P4 + P3L09	12.9	5.68	21.6	11.0

Weibull Parameters of Deuterium Concentration

	Cutoff PPM	Scale PPM	Shape
4 m All P4 + PL09	5	8.37	1.45
5 M High Power + P3L09	14	8.19	0.9

Weibull Parameters for Secondary Pick-up Rate
(Hydrogen Equivalent ppm per 7000 EFPH)

	Cutoff	Scale	Shape
4 m All P4 + P3L09	0	2.03	1.45
5 m High Power + P3L09	0.99	1.99	0.9

The expression for the cumulative probability for the Weibull distribution is given by

$$F(x) = 1 - \exp(-((x-c)/s)^n)$$

where c is the cut off, s is the scale parameter and n is the shape parameter.

TABLE 3

Input on the Threshold Values in PPM Hydrogen Equivalent

Pick-up Rates PPM/7000EFPH		Temperature (K) 520.20	543.20	568.20
0	MEAN	25.10	30.70	37.70
	S.D.	1.30	1.50	1.90
0.8	MEAN	33.50	37.10	42.50
	S.D.	2.25	1.95	2.60
4.0	MEAN	38.80	40.50	44.50
	S.D.	2.15	2.18	2.45
8.0	MEAN	46.70	46.40	48.80
	S.D.	2.70	2.60	2.70
12.0	MEAN	53.30	51.10	52.30
	S.D.	3.35	2.90	2.90
20.0	MEAN	65.00	59.20	58.30
	S.D.	4.80	3.60	3.35
40.0	MEAN	92.80	75.50	70.10
	S.D.	9.00	5.30	4.35

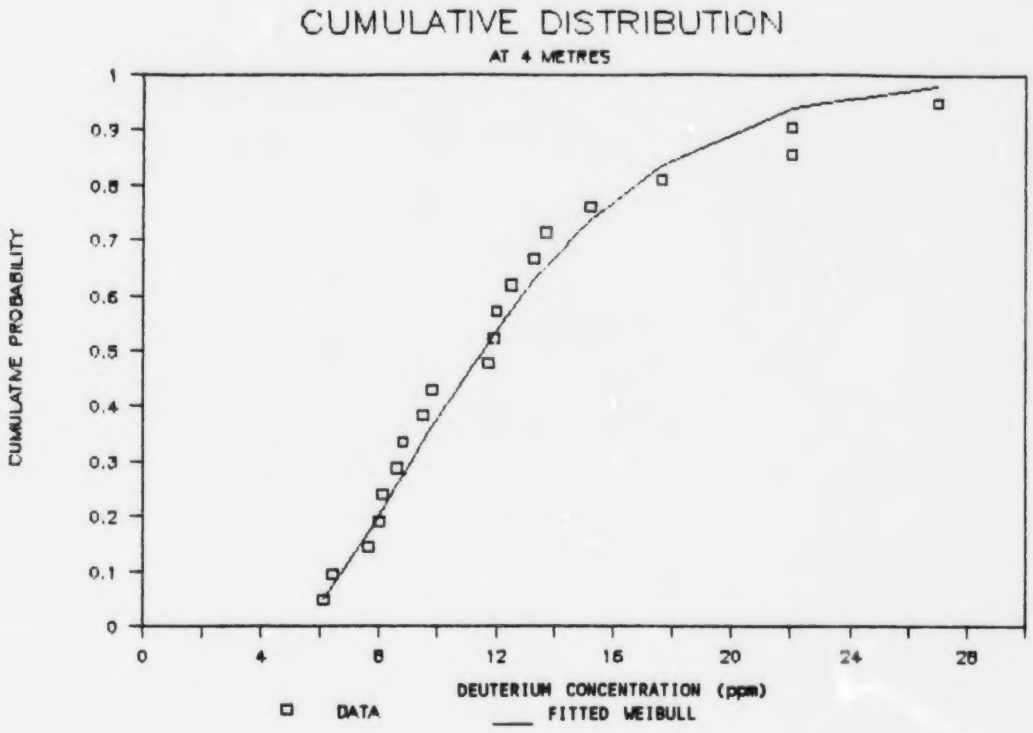

FIGURE 1.

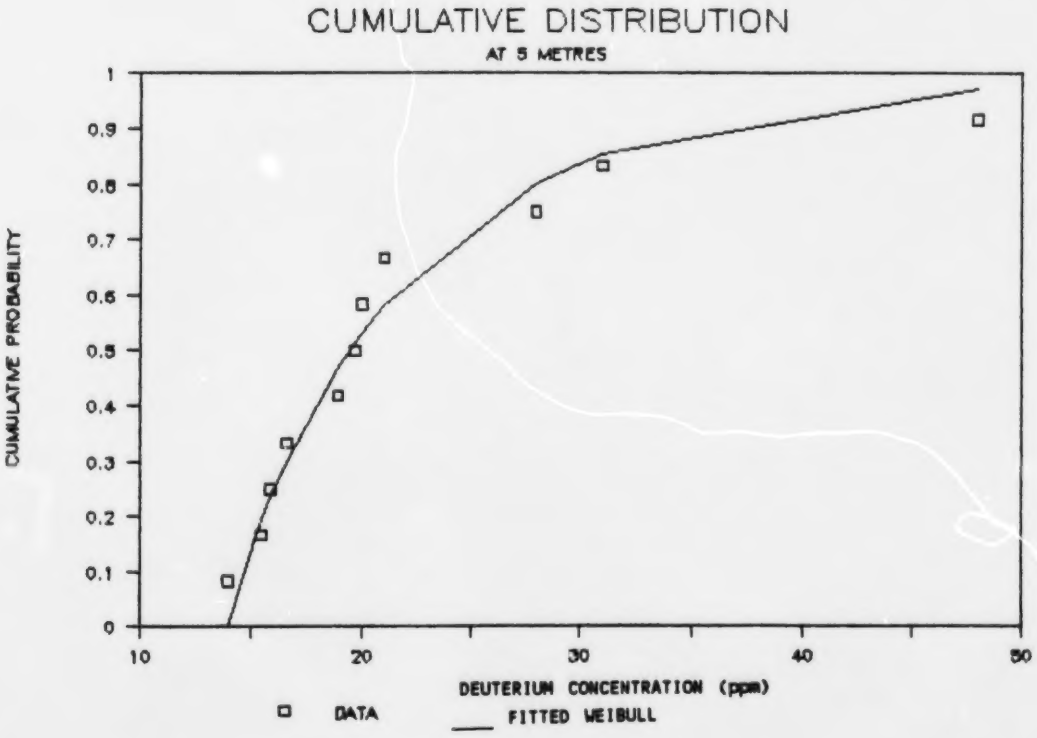

FIGURE 2.

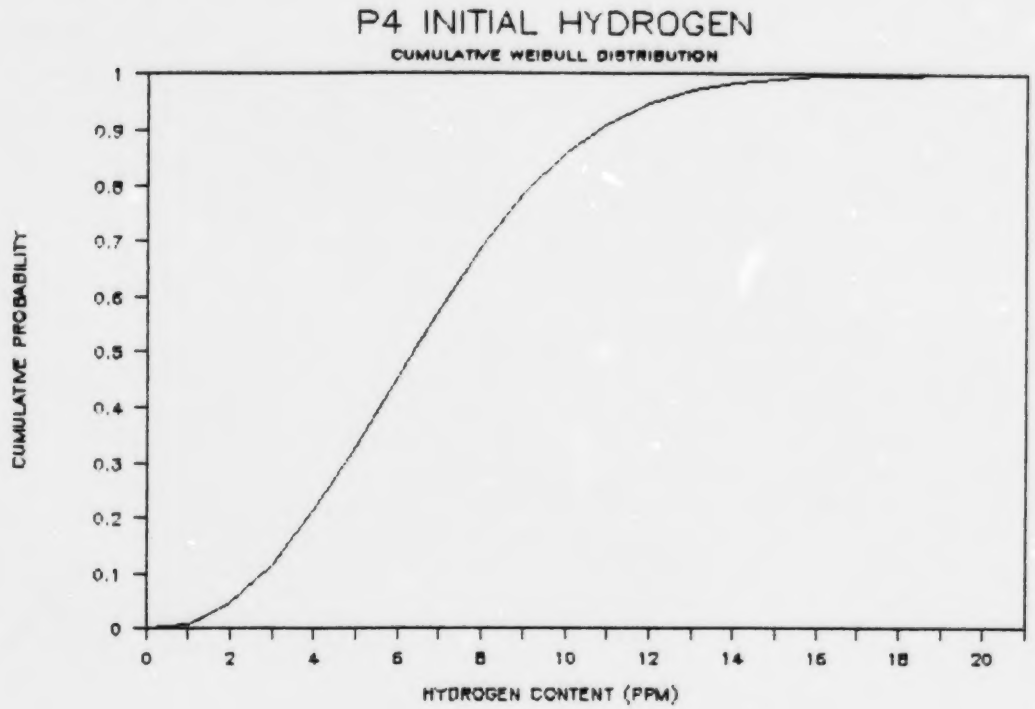

FIGURE 3.

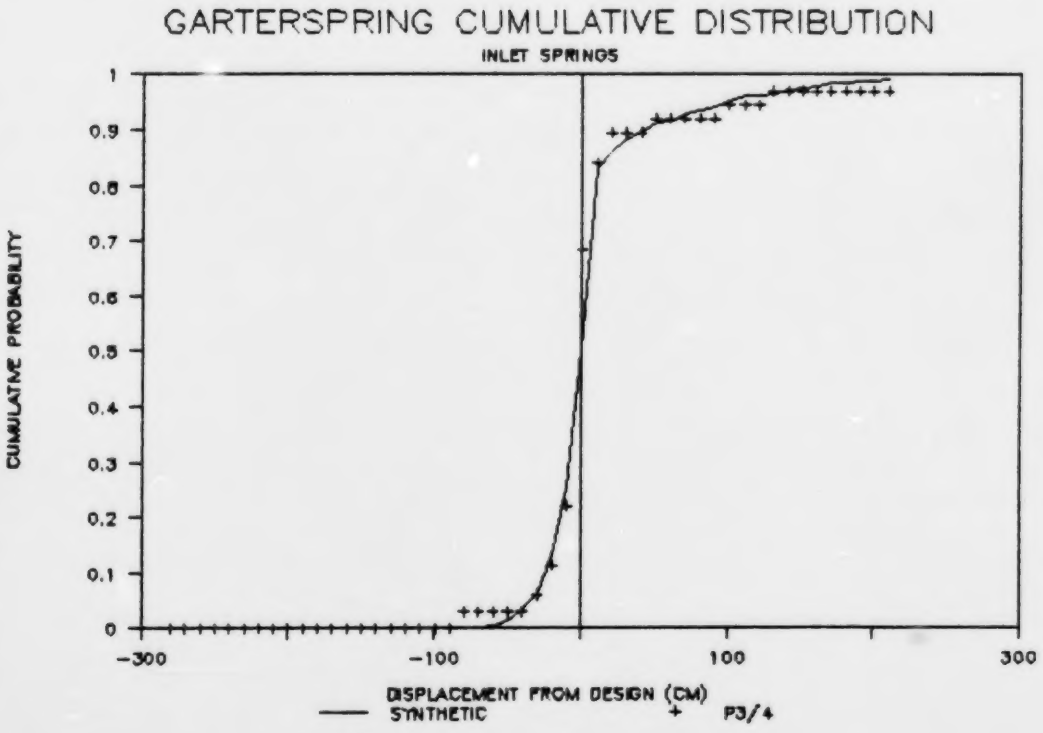

FIGURE 4.

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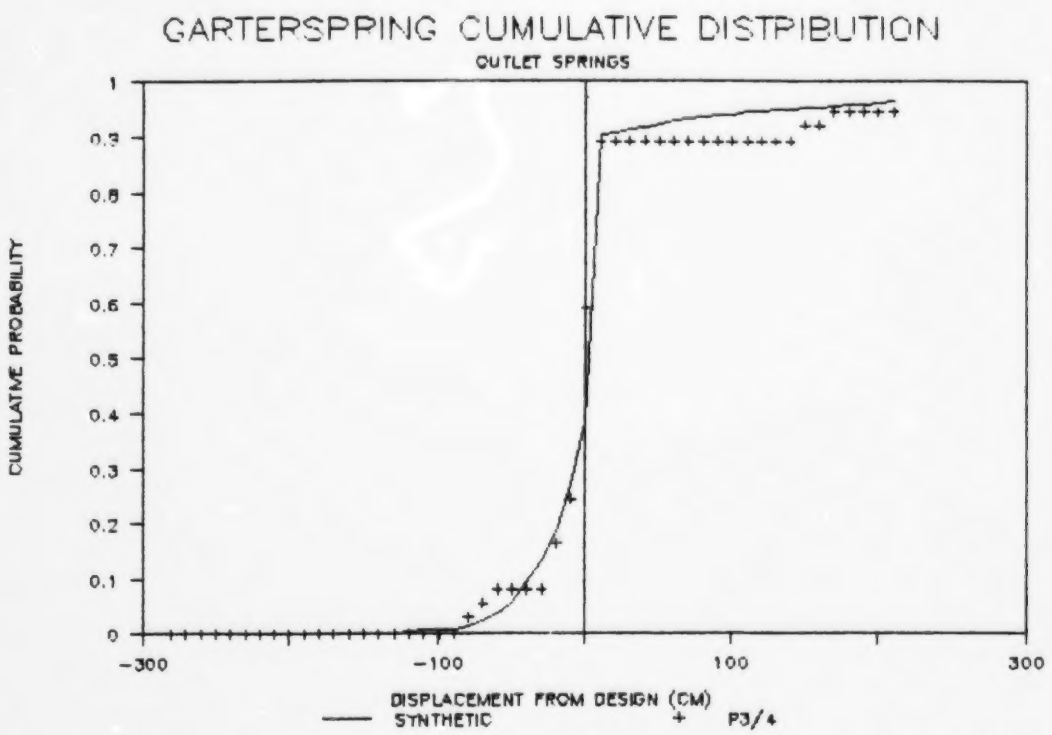
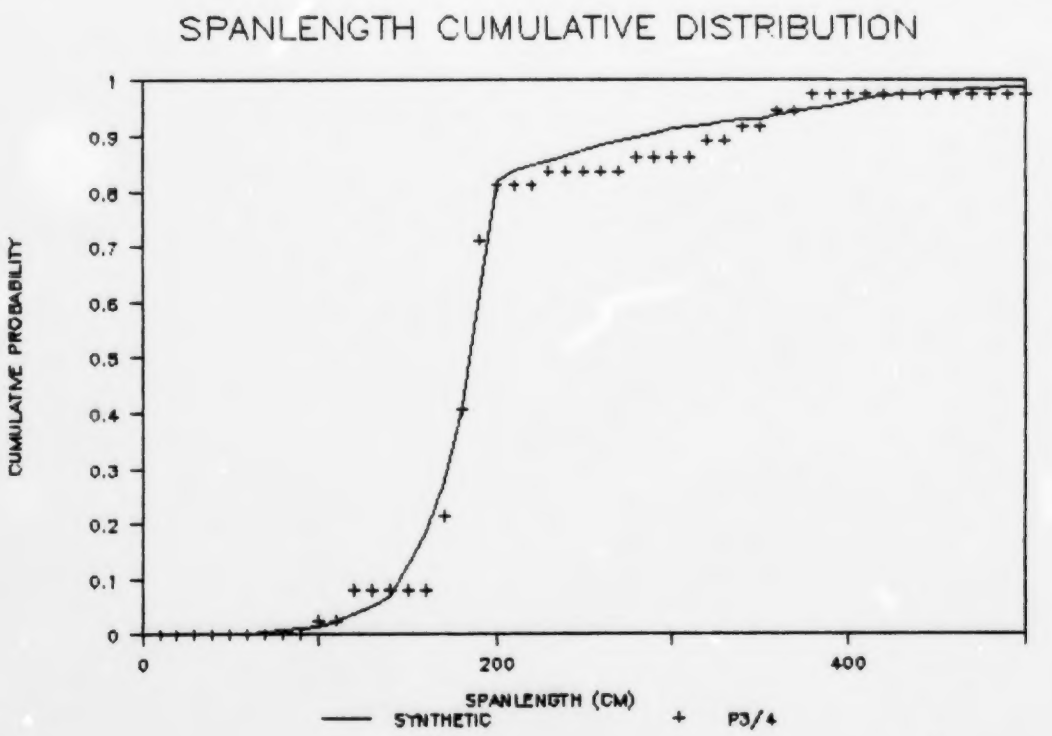


FIGURE 5.



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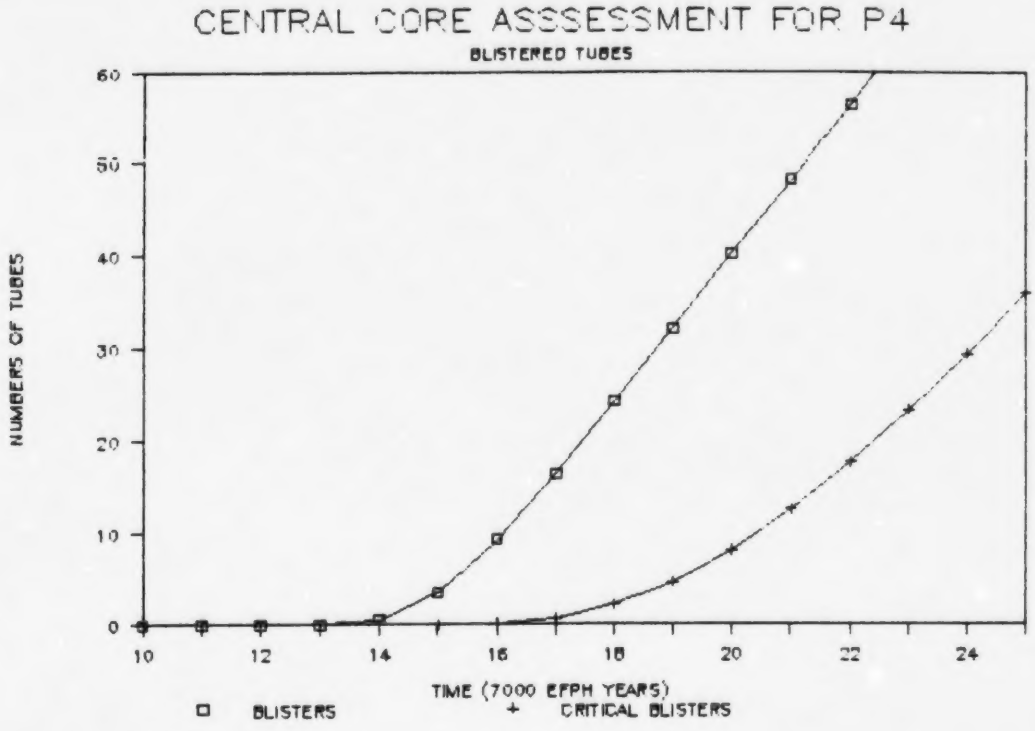
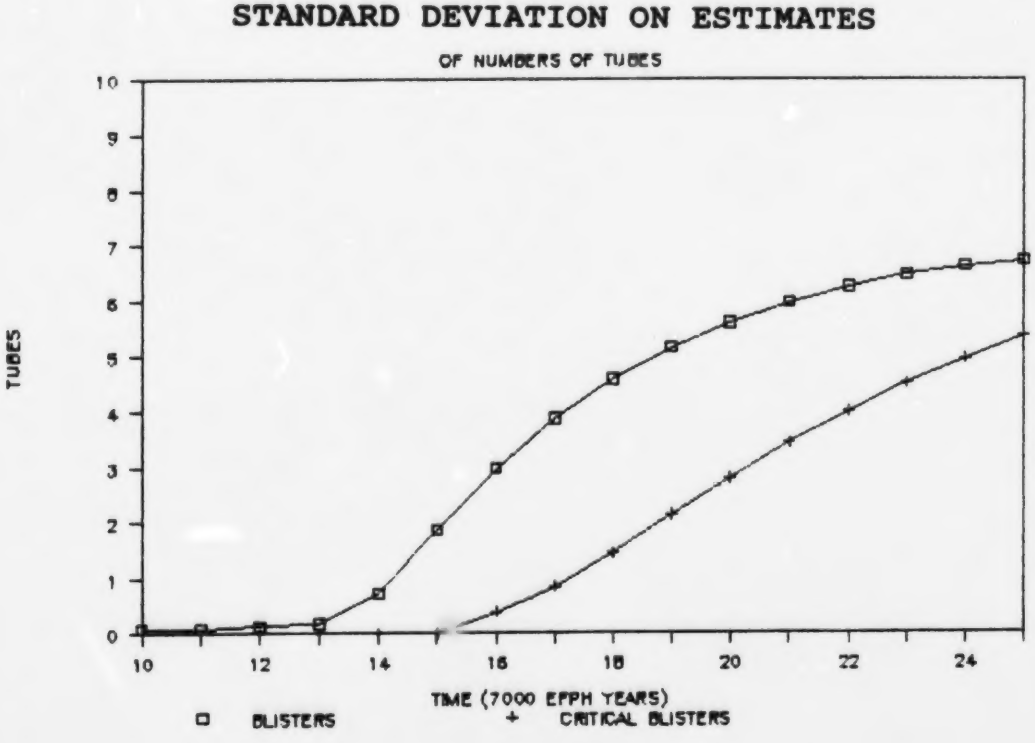


FIGURE 7.



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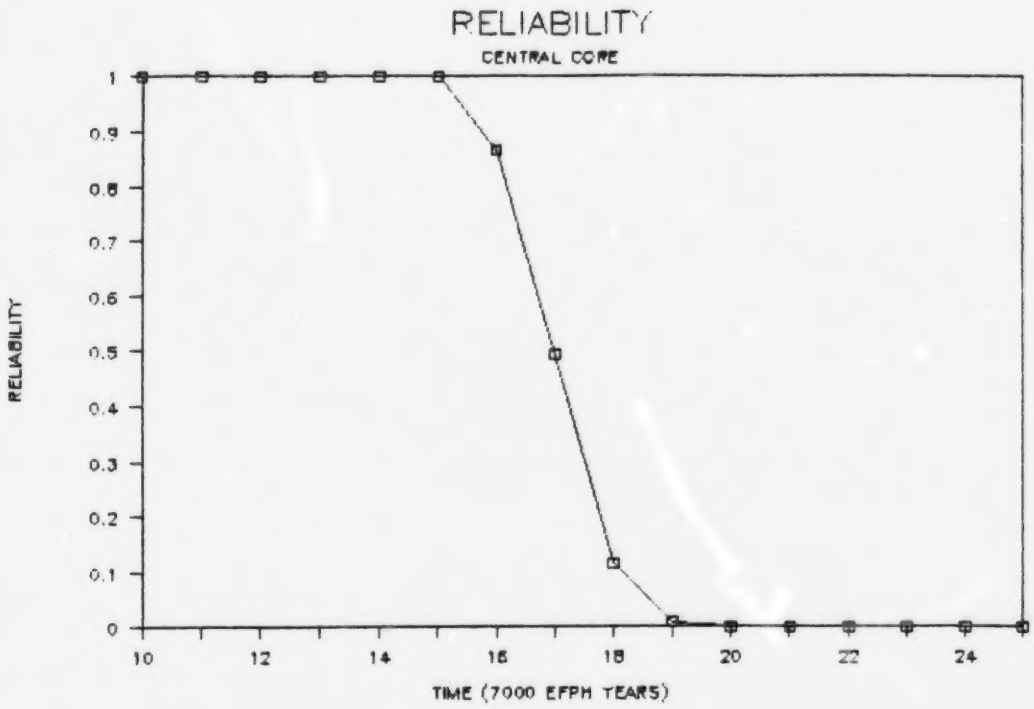

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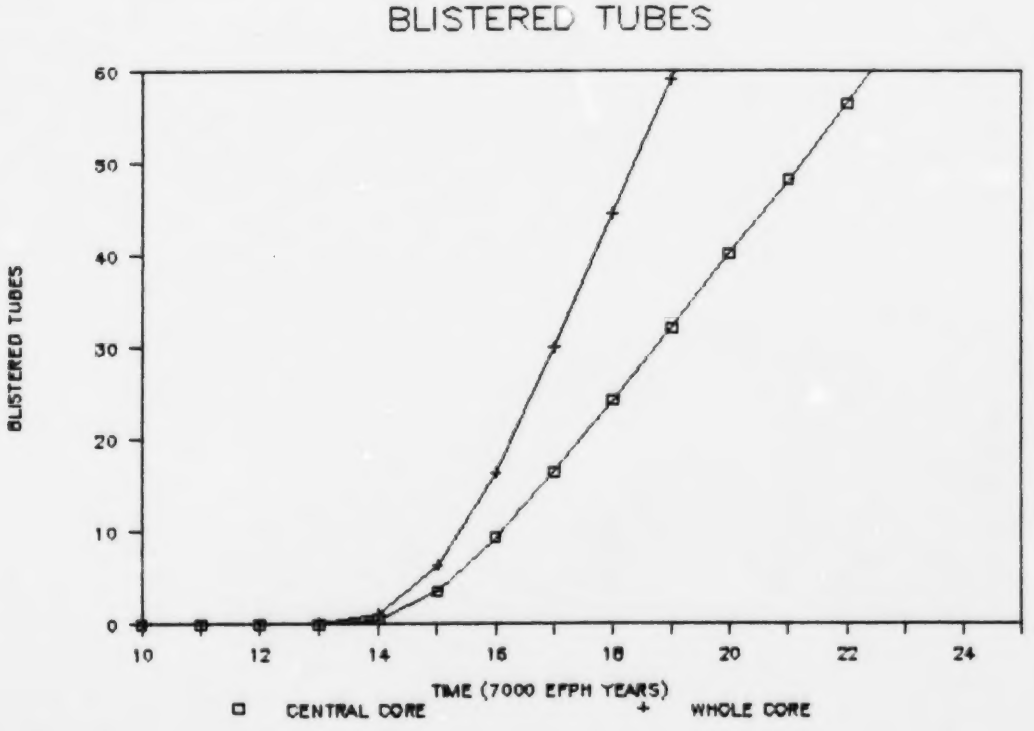

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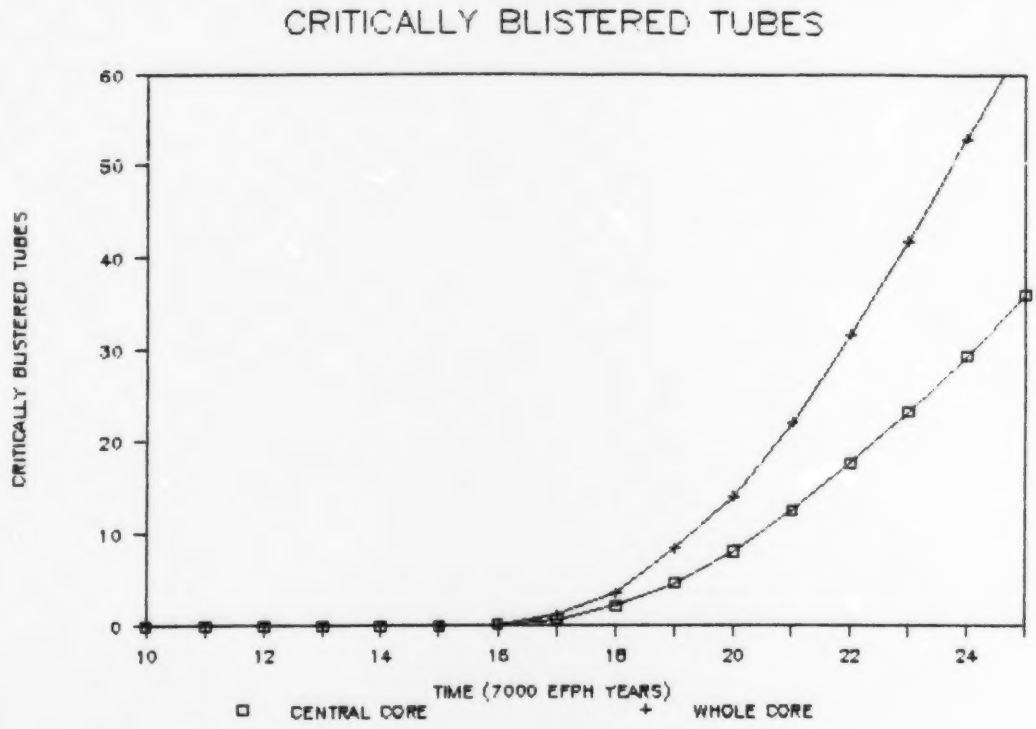

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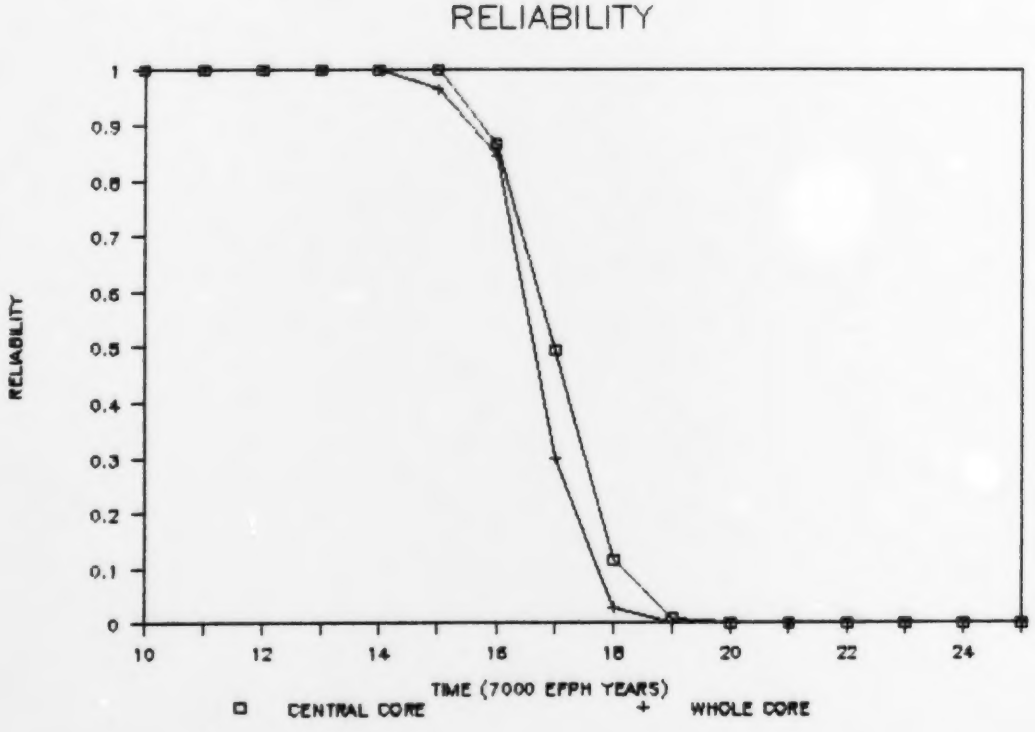

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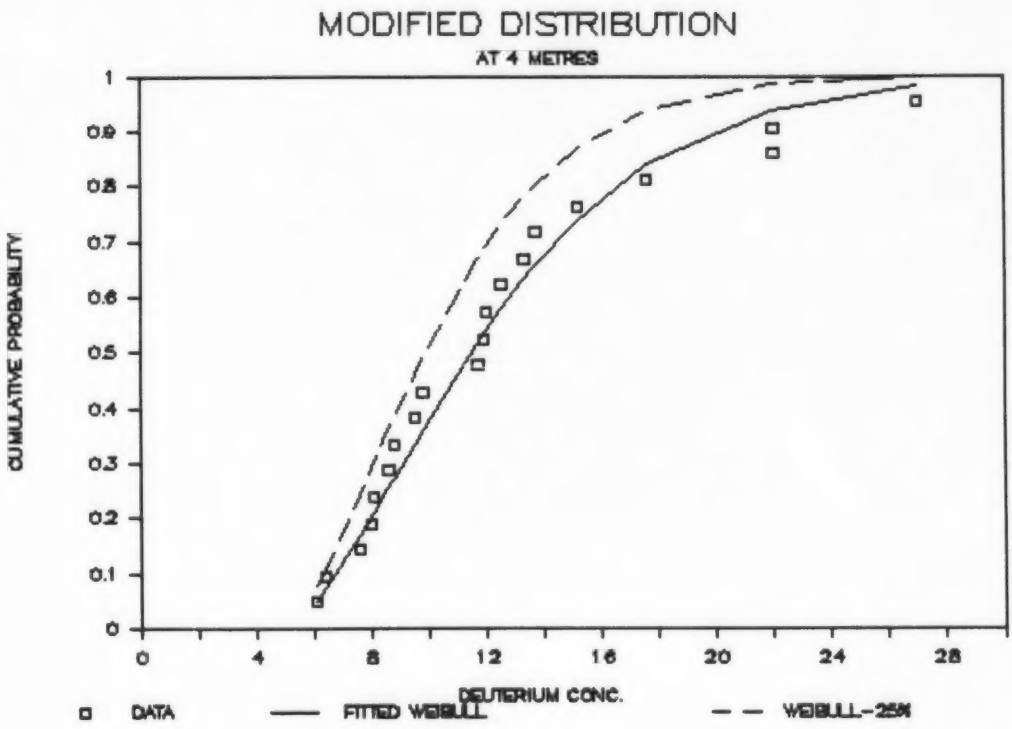


FIGURE 13

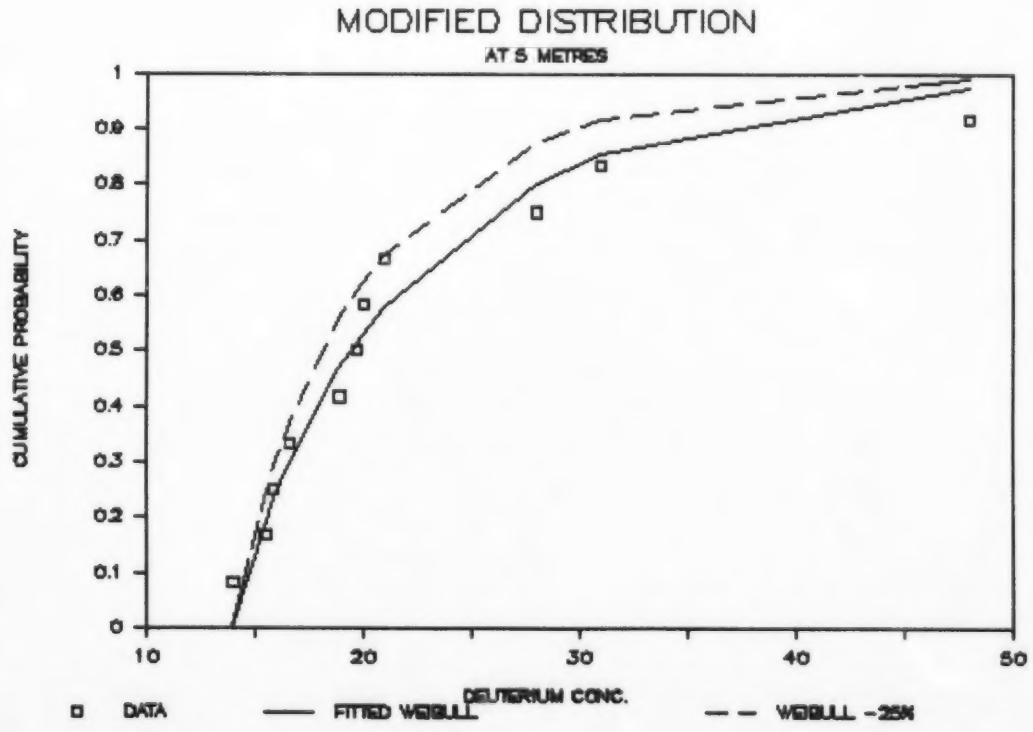
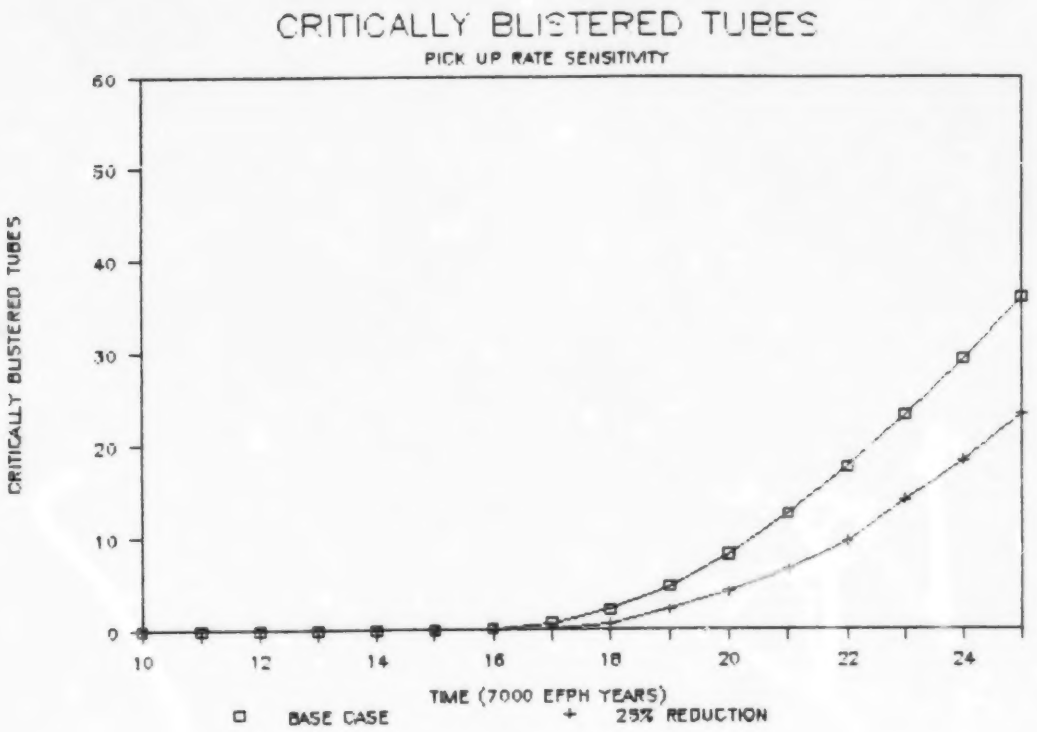


FIGURE 14



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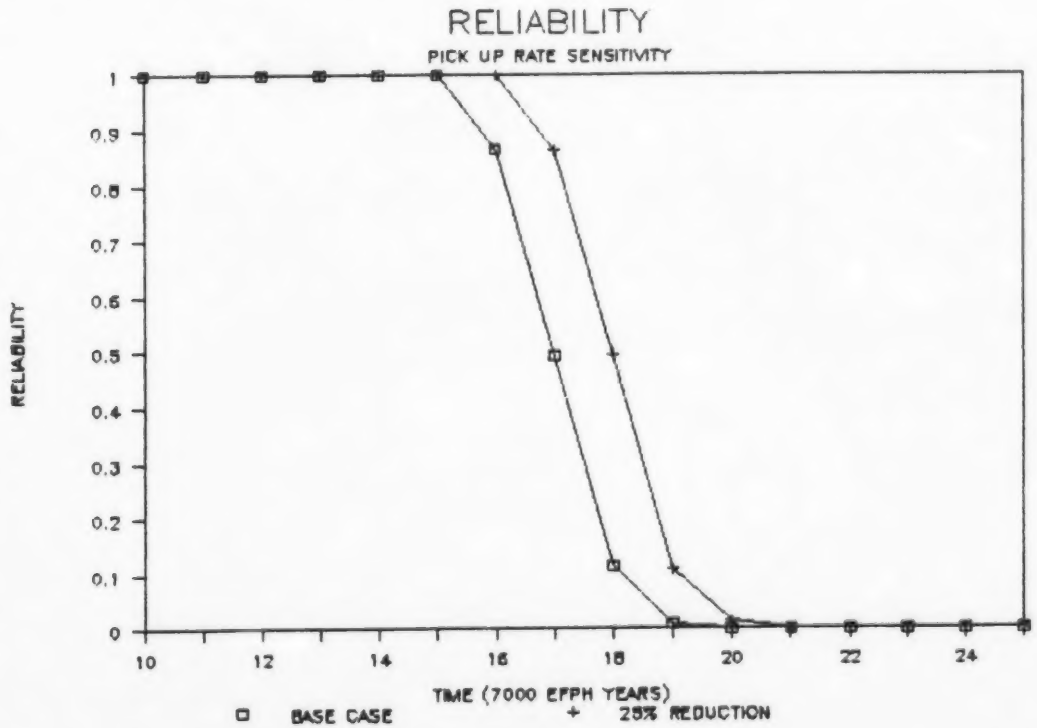

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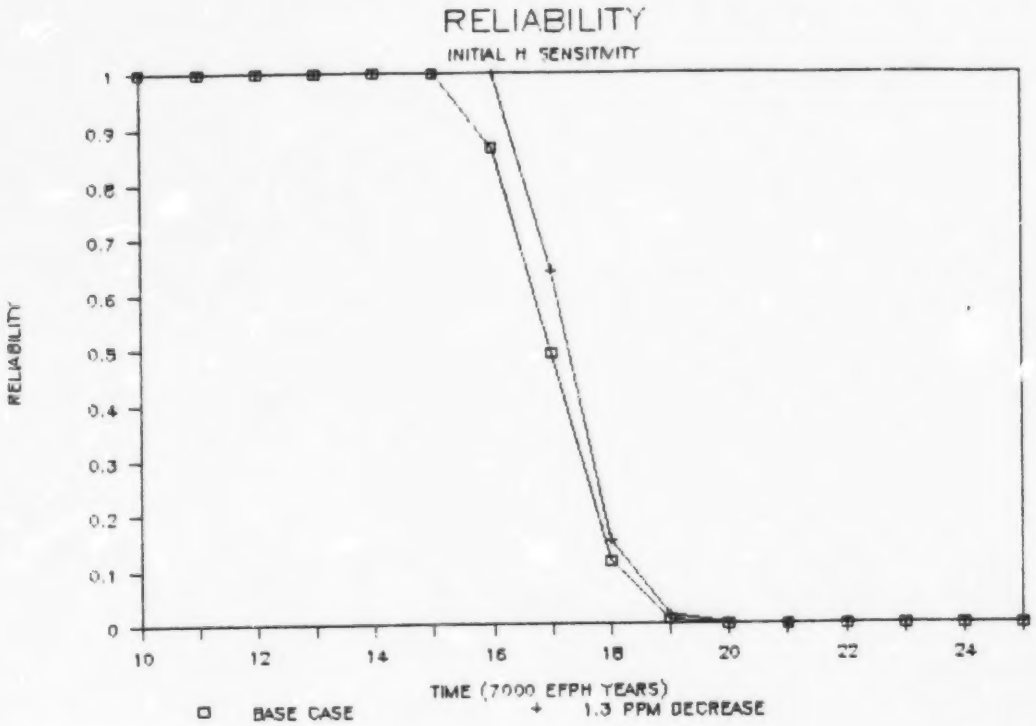
RELIABILITY
INITIAL H SENSITIVITY
RELIABILITY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
12
14
16
18
20
22
24
TIME (7000 EFPH YEARS)
BASE CASE
1.3 PPM DECREASE

FIGURE 17.

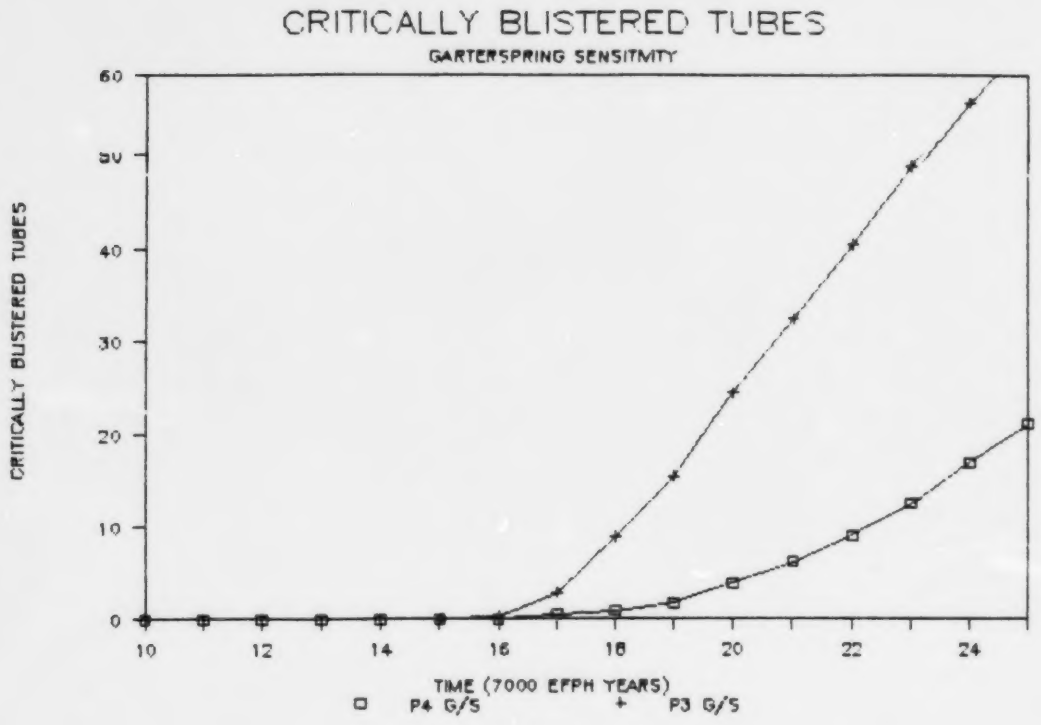

FIGURE 18.

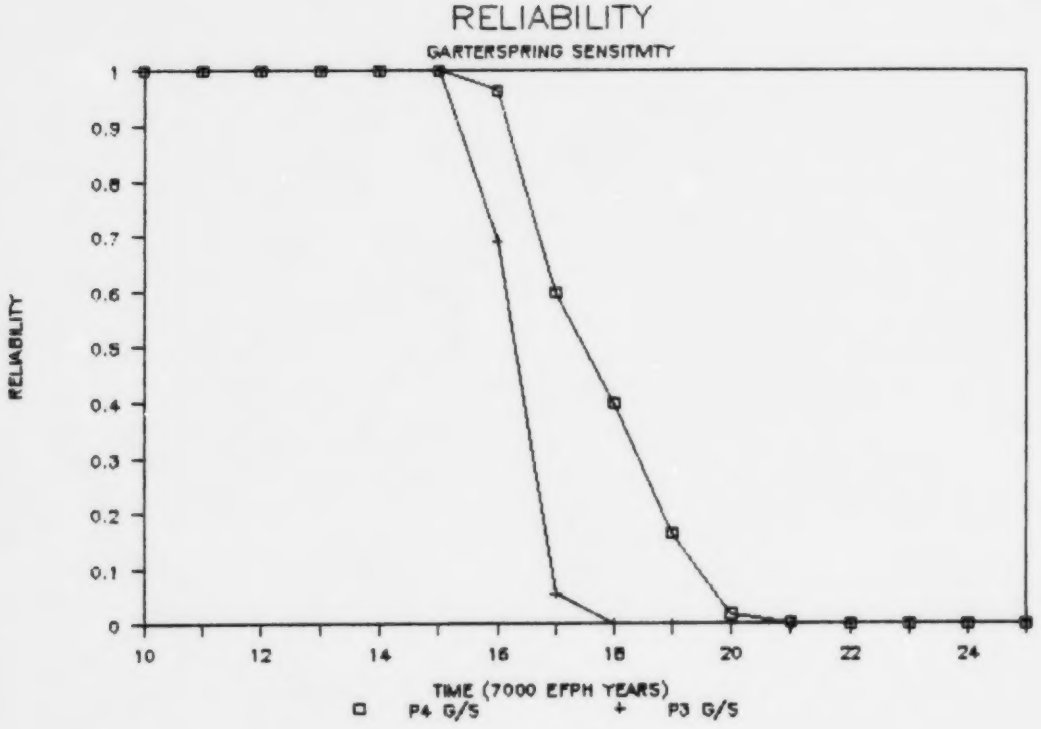

FIGURE 19.

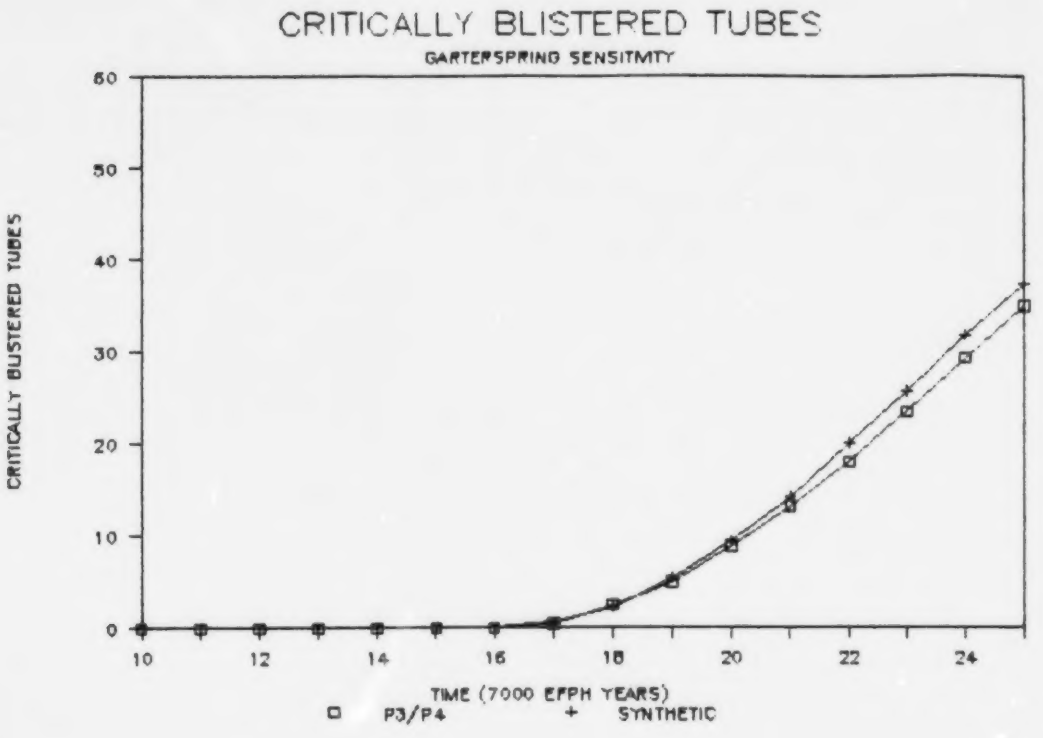

FIGURE 20.

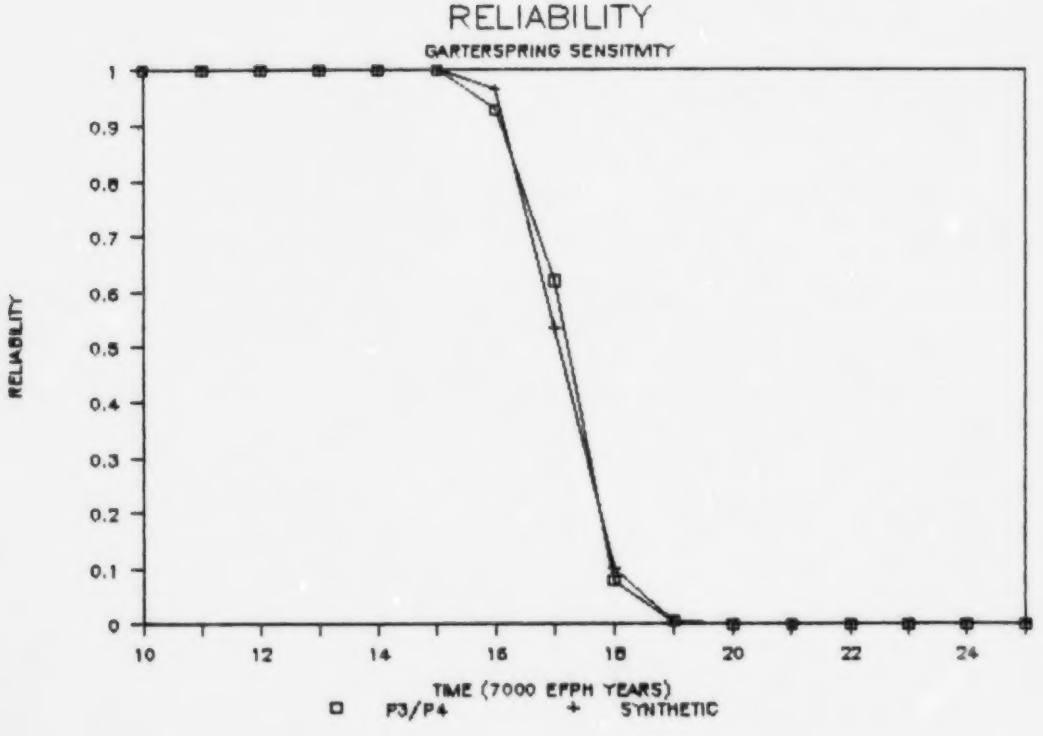

FIGURE 21.

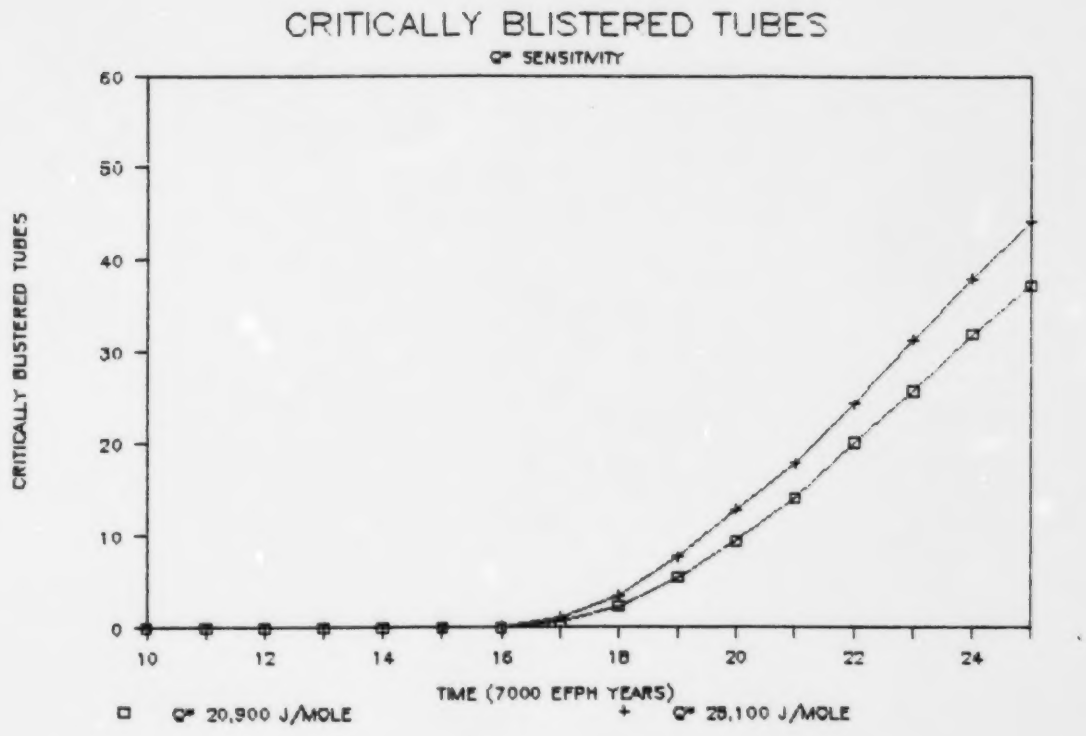

FIGURE 22.

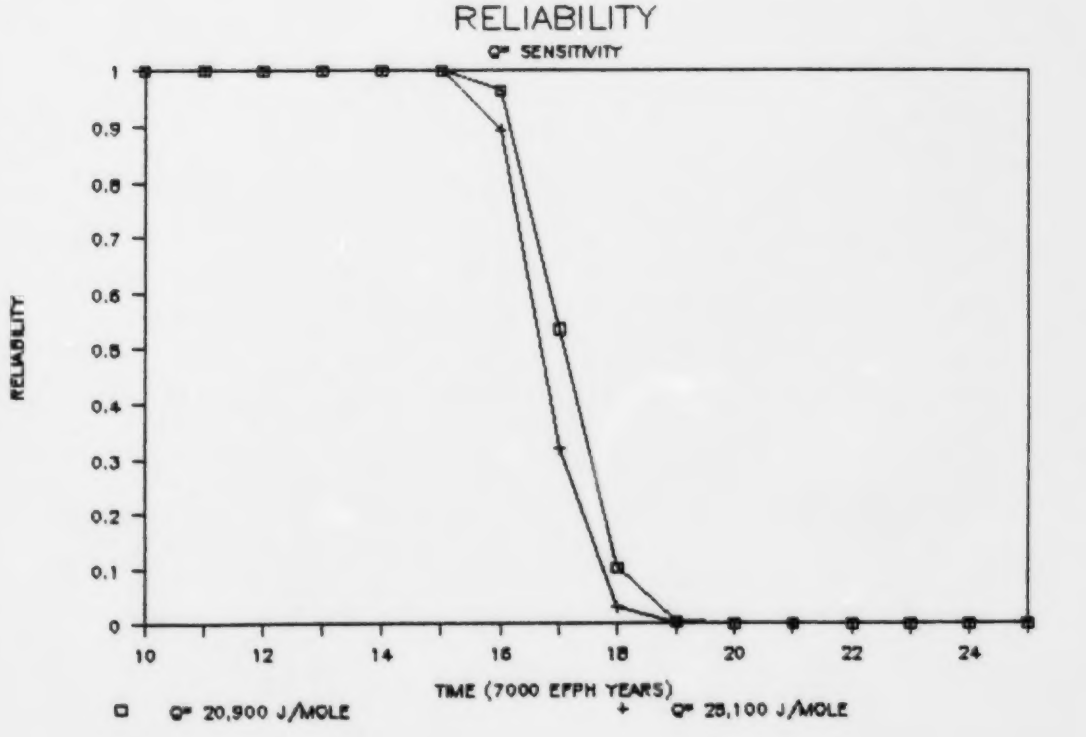

FIGURE 23.